

Interdecadal Change in the Asia-Africa Summer Monsoon and Its Associated Changes in Global Atmospheric Circulation

X.-W. Quan, H.F. Diaz

(NOAA-CIRES Climate Diagnostic Center, 325 Broadway, Boulder, Colorado, U.S.A.)

C.-B. Fu

(Institute of Atmospheric Physics, Chinese Academy of Science, Beijing, P.R. China)

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Abstract

Previous studies have noted that summer precipitation in the sub-Saharan region of North Africa showed a large decrease around the year of 1968, and this drought has persisted for much of the period since then. A trend toward decreased summer precipitation is also observed in northeast China. A decrease in precipitation over northeastern China also began around 1968. In this study, we examine the changes in atmospheric circulation that are associated with the interdecadal changes in summer precipitation over Asia and Africa. Data from the reanalysis project by the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP Reanalysis) are used. Precipitation based on the NCEP Reanalysis are compared to precipitation observed at stations in China and the sub-Saharan region. We found that the NCEP reanalysis precipitation represents well both the sign and timing of the observed (in situ) change in the summer precipitation over North Africa, as well as the spatial pattern of the observed precipitation changes over eastern China. We have also examined corresponding changes in 850 mb and 200 mb divergent and rotational circulation features in the NCEP reanalysis. The persistent drought over the sub-Saharan North Africa (the Sahel region) is accompanied by pronounced intensification of divergence (convergence) in the lower (upper) troposphere above the region. The persistent drought in the Sahel is related to changes in the Asia summer monsoon in two ways: (1) In the tropics, the intensification of the lower level divergence is accompanied by stronger convergence over southeast Asia where summer precipitation increased. The changes in the divergent circulation implies an interdecadal change in the zonal circulation in the tropics, with stronger convergence over the southeast Asia leading to an intensified Hadley cell over east Asia, and associated stronger descending motion and lower level divergence over the region of northeast China; and (2) The persistent drought over the north Africa became a source of planetary wave activity that helped in the development of stronger anticyclones over northeast China and the south Indian Ocean.

1. Introduction

Previous studies have noted that the summer monsoon over the Sahel region in Africa and in Southeast Asia have exhibited significant changes around the mid- to late-1960's. Lamb (1982,1983) found that precipitation over the Sahel region decreased sharply starting around 1968 with drought persisting throughout the 1970's and 80's. Guo (1983) and Fu *et al.* (1989) noticed that the period of Mei-Yu (Plum Rains) had shortened during this period, and the intensity of the summer monsoon weakened over Southeast Asia. Other studies have shown that climate changes in the monsoon region during the mid-1960's were accompanied by changes in other aspects of large-scale climate, such as surface cooling over North America (Diaz, 1986) and in the Northern Hemisphere (Dronia, 1974), and changes in spatial pattern of 500 mb height and sea level pressure (Yan *et al.*, 1989). Allan *et al.* (1995) found that the semi-permanent anticyclone in the mean flow field of the atmosphere over the southern Indian Ocean in the season of January-February-March (JFM) intensified after 1962. In this paper we consider the following questions. What are the principal characteristics and possible mechanisms associated with decadal-scale change in the summer monsoon system in the region from North Africa to Southeast Asia? What mechanism can keep a certain mode of the monsoon circulation pattern to prevalent over decades? How does the change in monsoon system relate to the decadal change over the Pacific Ocean? (see, e.g., Graham and Barnett 1994, Trenberth and Hurrell, 1994, Wang, 1995, Zhang *et al.*, 1996).

The data and methods are briefly described in section 2, interdecadal changes in the precipitation over the east Asia and the north Africa are shown in section 3, analysis of interdecadal changes in divergent flow is presented in section 4; the changes in rotational wind circulation patterns are presented section 5; discussion and conclusions are given in section 6.

2. Data and Method

We present an analysis of the 50-year NCEP Reanalysis data set (Kalnay *et al.*, 1996) in conjunction with independent station precipitation records. The NCEP Reanalysis data is a product of assimilating real observations into an atmospheric general circulation model (AGCM) which covers the period from January 1948 to October 2000. It has the advantage of complete 4-dimensional coverage in space and time. Some of the variability contained in the NCEP reanalysis data may be model dependent because the gaps where original observations did not cover are filled with values generated by the AGCM. It has been noticed that changes in the NCEP reanalysis data may due to some artificial effect in the process of reanalysis, e.g. the changes in what kind of data and/or how the data are assimilated in to the model. To examine how well the reanalysis data represent real climate changes, station observations are used as independent means of verification.

To analyze the changes in atmospheric circulation, we calculate velocity-potential (ϕ) and stream-function (ψ), which are defined as $\nabla^2\phi = \nabla \cdot \mathbf{v}$ and $\nabla^2\psi = \nabla \times \mathbf{v}$, where \mathbf{v} is

the two-dimensional horizontal wind vector, and examine the difference between two multi-decadal periods: 1948 to 1967 and 1968 to 1999. All the analysis are performed on seasonal means for the three months of northern summer: June, July, and August (JJA).

3. Interdecadal Changes in the Summer Monsoon over East Asia and North Africa

Comparison of the observed precipitation with the NCEP reanalysis precipitation is shown in Figures 1 to 3. Figure 1 shows the spatial pattern of interdecadal change in summer (JJA) precipitation over China. Each square represent one of the 205 meteorological or hydrological stations in China (Tao et al, 1991). The signs represent the difference between the temporal averages of mean JJA precipitation for two multi-decadal periods: 1948-1967 and 1968-1993. A plus (+)/minus (-) sign indicates that the average of summer precipitation for the later period is larger (smaller) than the average for the earlier period by more than 10 mm/month, and a gray colored square with no sign means the difference between the two periods are less than 10 mm/month. The interdecadal change in the summer precipitation over east China (e.g., east of 110°E) exhibits a dipole pattern. Summer precipitation decreased in north China (north of 30°N) but increased in the south China (roughly between 25°N and 30°N). This dipole structure is relatively well captured in the NCEP reanalysis data (Fig.2). Time series of JJA mean precipitation at selected locations are compared in Fig. 3. Figure 3a compares the precipitation of NCEP reanalysis with the observations by HeZe (35°N, 115°E) and HuangShi (30°N, 115°E) stations of China highlighted by the signs of larger size in Fig.1). A Change around the mid-1960's is evident from frequent positive anomalies in the earlier period to frequent negative anomalies during the latter period in both the precipitation at the HeZe station and the NCEP reanalysis precipitation at (35°N, 115°E). Precipitation observed at the HuangShi station shows positive anomalies appeared more frequently in the later period. This trend is also captured by the NCEP reanalysis, but the change in the NCEP reanalysis precipitation at (30°N,115°E) is somewhat exaggerated compared to the change in the actual observations. Figure 3b compares the area mean precipitation of reanalysis over the Sahel (10°N-20°N, 0°-20°E) with the Sahel rainfall index published by Lamb (1982, 1983) shown for comparison. A dramatic transition from wet to dry climate during the mid-1960's is evident in both time series, although the positive anomalies in the reanalysis precipitation appear to be rather large for the years of the late 1950's to late 1960's compared with the observations. Our judgment is that the NCEP reanalysis data have captured reasonably well the interdecadal changes in the summer precipitation over the monsoon region in Asia and Africa in the mid-1960's, although the changes have been somewhat exaggerated in the reanalysis data. Below we present further analysis on the mid-1960's climate change using the NCEP reanalysis data. Our goal is to examine some of the key process associated with this major decadal climate change, including potential sources of error that leads to bias the reanalysis data.

4. Interdecadal Change in Divergent Wind Circulation

For the purpose of diagnosing changes in the atmospheric circulation, examining the divergent wind has at least two advantages, especially for the circulation in the tropics: (1) divergent wind directly links to vertical motion, which is in turn sensitive to changes in local surface conditions; (2) the divergent wind provides a good way to depict overturning circulation such as the zonal Walker circulation in the tropics and the Hadley cell in meridional circulation. A detailed analysis on the annual cycle in global divergent wind circulation can be found in Trenberth et al. (1998), in which the authors examined two 25-year (1979-93) climatologies of reanalysis data, one by NCEP and the other by the European Center for Medium-Range Weather Forecast (ECMWF).

The interdecadal change in the JJA mean divergent wind circulation from the period of 1948-67 to the period of 1968-99 is illustrated in Fig. 4. The interdecadal change in the divergent circulation in upper troposphere (200 mb) has a simple structure of two pairs of divergent/convergent centers. In the upper troposphere, convergence (and therefore enhanced sinking motion) is intensified in the latter period over North Africa and central tropical Pacific ocean; and divergence (indicative of enhanced convection) is enhanced over the tropical zone of South America and (to a lesser degree) Southeast Asia (Fig. 4a). The interdecadal change in the divergent circulation in lower troposphere (850 mb) shows, as expected essentially a mirror image of the pattern in the upper level, but with sign reversed. In the lower troposphere, stronger divergence is seen in the later period over the north Africa and central tropical Pacific ocean (Fig. 4b), and stronger convergence over the southeast Asia and the tropical zone from the eastern tropical Pacific ocean to the coast of Brazil. In addition, a zone of enhanced low level divergence is seen over the north part of central to eastern Asia, which indicates the development of drought over the northeast Asian region. The intensification of the lower level divergence over northeast Asia and the lower level convergence over southeast Asia implies that the Hadley Cell in the meridional circulation over east Asia intensified in the latter period. On the other hand, the changes in the divergent circulation also imply adjustment of transverse circulation over the global tropics: descending motion became more prevail over northern Africa and the central tropical Pacific Ocean in the later period while ascending motion was enhanced over Southeast Asia, the east tropical Pacific Ocean, and in South America. The stronger ascending motion over Southeast Asia and descending motions over the central tropical Pacific implies a westward shift of the Walker Circulation. The magnitude of the changes in the low-level divergence over the tropical Pacific and the low-level convergence over the South America seems a bit too large in the NCEP reanalysis. It is possible that the intensification of subsidence over the central tropical Pacific Ocean has been somewhat exaggerated in the NCEP reanalysis data (see section 6 for further discussion on the impact of possible system biases in the NCEP reanalysis).

One might attribute the westward shift of the Walker Circulation as a response of atmospheric circulation to the changes in sea surface temperature (SST) in the tropical Pacific ocean. That suggestion appears to be wrong in this case, because the interdecadal change over the tropical Pacific ocean has been shown to occur a few years later than the time when the above changes took place over the relevant portions of North Africa and

Southeast Asia. The time series of JJA mean velocity potential of 200 mb over north Africa (5°N-25°N,10°E-45°E), southeast Asia (5°N-15°N,100°E-120°E), central tropical Pacific ocean (10°S-10°N,180°E-160°W), and tropical South America (10°S-10°N,80°W-40°W) are shown in Fig. 5. Here, positive (negative) anomalies of the velocity potential means weaker (stronger) than average convergence. It is clear that a transition from weak to strong convergence had taken place over the region of north Africa around 1968 (top panel), well before the transition over the central tropical Pacific ocean in early- to mid-1970's (bottom panel). In the time series of the 200 mb velocity potential over Southeast Asia, an increase of positive anomalies is also evident around 1968. Judged by the timing of when these changes occurred, it is more likely that the intensification of the ascending motions over the southeast Asia are linked to the intensification of descending motion over the north Africa via the change in monsoon circulation, which leads the adjustment of the Walker circulation over the tropical Pacific Ocean.

5. Interdecadal Change in Rotational Wind Circulation

The rotational wind circulation is largely determined by the balance between the Coriolis force and the force due to gradient in the horizontal pressure field. The gradients in pressure field can be sensitive to perturbation in remote locations via atmospheric wave propagation. Therefore, a change in rotational wind circulation in a certain place does not always have to be a reflection of changes in local surface condition. In this section we will show that in the NCEP reanalysis data the interdecadal changes in the mean JJA rotational wind circulations over the south Indian Ocean and the tropical Pacific Ocean is already evident in the mid-1960's which is a few years earlier than the changes documented in Pacific Ocean SST.

The spatial pattern of the difference in JJA mean rotational circulations for the periods before and after 1967 are shown in Fig. 6. As reflected in the upper troposphere streamfunction, a pair of cyclonic circulation features intensified over the north subtropical Atlantic Ocean and northwest Africa (25°N-40°N, 40°W-15°E), in the tropical to subtropical region in southern Africa (0°S-30°S,0°-60°E), and the eastern portions of South America (0°-25°S,70°W-30°W). In the northern mid-latitudes, cyclonic circulations also intensified over northeast China and Siberia (45°N-65°N,110°E-150°E). In the Southern Hemisphere, anticyclonic circulation increased over the South Indian Ocean (35°S-55°S, 30°E-100°E) which appears to be part of a wave train emanating from the tropics in Africa. Another wave train is seen over the South Pacific Ocean with intensified cyclonic circulation over the central tropical Pacific Ocean (0°-30°S, 180°-140°W), and a stronger anticyclone over the southern midlatitudes (30°S-50°S, 160°W-110°W). At lower levels, the 850 mb streamfunction differences (Fig. 6b), show a pair of anticyclonic circulations over the tropical and subtropical Africa (primarily over the Sahel). Anticyclonic circulation also became stronger over the South Indian Ocean, and the northeast China and Siberia. At the lower level, cyclonic circulations became stronger over Southeast Asia and a pair of stronger cyclonic circulation features are seen over the

tropical Pacific Ocean. The intensification of the anticyclone over northeast China and the cyclone over southeast Asia also helps to explain the dipole pattern of drought in north, wet in south seen in the interdecadal change of summer precipitation over eastern China (Fig. 1). Over the coasts between the Antarctic continent and Pacific ocean (55°S-80°S, 160°W-100°W), a cyclonic circulation become very strong in the 1968-99 period.

Time series of the streamfunction for the JJA mean rotational wind circulation at 200mb are shown in Fig. 7. As expected, the changes in the rotational wind circulation over northern Asia (35°N-50°N, 110°E-130°E), northern subtropical Atlantic Ocean (25°N-30°N, 40°W-0°), and southern Africa (15°S-30°S, 0°-60°E) occurred at about the same time when the changes in the divergent circulation over Asia and Africa took place (Fig.5). Interestingly, the interdecadal change in the rotational wind circulation over the Pacific Ocean and South America also started in the late 1960's which leads by a few years the changes in local divergent circulation (Fig. 5). A number of previous studies have reached a similar conclusion that the eastern tropical Pacific Ocean had become warmer in the past couple of decades, and that the timing of a significant transition in SST occurred around the mid-1970's (Graham and Barnett 1994, Trenberth and Hurrell, 1994, Wang, 1995, Zhang *et al.*, 1996). The difference in the timing of the change in the rotational wind circulation and the change in the tropical Pacific SST suggest that the changes in wind circulation shown in this study were not initially forced by the changes in Pacific Ocean SST. Instead, the earlier development of the low level cyclones over the tropical Pacific Ocean and extending to South America may have contributed to the development of a regime of higher SST in the eastern tropical Pacific Ocean.

6. Summary and Discussion

The interdecadal changes in the NCEP reanalysis data analyzed here have the following major features. Despite the existence of some biases in the earlier data, the changes in the precipitation of the NCEP reanalysis documented here agree well as to timing of changes and sign of trends with in situ observations over eastern China and the Sahel region of Africa. The spatial pattern of the changes in NCEP reanalysis precipitation is also well represented compared to station-derived changes in precipitation over east China. Examples of some degree of bias are: 1) the summer precipitation is a somewhat higher over the Sahel region in the NCEP reanalysis data for the period from late 1950's to late 1960's compared to Lamb's sub-Sahara rainfall index; and 2) the increase in summer precipitation over southeast China is somewhat exaggerated in the NCEP reanalysis.

Associated with the interdecadal changes in precipitation over Africa and Asia, summer monsoon low-level divergence became stronger over northern areas of Africa, while low level convergence became stronger over southeast Asia. Correspondingly, the upper level convergence became stronger over northern Africa, and the divergence in the upper troposphere was intensified over the southeast Asia. In addition, divergence in the lower troposphere became stronger over central to eastern parts of east Asia. We find that the

transition of climate regime in the monsoon circulation occurred a few years before the change in the Walker circulation over the tropical Pacific ocean.

The intensification of anticyclone/cyclone pairs in the lower/upper troposphere over the tropical to subtropical Africa is a striking feature of the interdecadal change in the rotational wind circulations. The persistent drought in the Sahel region appears to generate planetary wave circulations that may have helped to intensify anticyclonic circulations over the south Indian ocean and in northeast China.

Below we further consider some possible causes of this transition in the global atmospheric circulation in the mid- to late-1960's.

Systematic error in data

We do not feel that the interdecadal changes seen in the NCEP reanalysis data are caused by systematic error. Systematic error may be introduced into the reanalysis data in three possible ways:

Possible biases exist in the original observations

Such biases might have been induced by two systematic changes in observational methods: (a) The change in rawinsonde launch time since the June of 1957; (b) The use of satellite observations since 1979. The timing of both these changes do not match the timing of the interdecadal changes discussed in this paper. Thus the impact of possible biases of this type can only be a minor factor in this regard.

Possible errors in the reanalysis process

A number of errors in the NCEP reanalysis have been identified. Lists of the known error sources can be found in the web-page of NCEP (<http://wesley.wwb.noaa.gov/reanalysis.html>), NCAR (<http://dss.ucar.edu/pub/reanalysis>), and a web page by Kistler (<http://lnx21.wwb.noaa.gov>). Many of these errors have been corrected, some have not. So far, among the known errors, the "PSFC problem" and "Spurious moisture sink/source" may have possible impact on the interdecadal changes in the NCEP reanalysis data. Description and assessment of the impact of the PSFC-problem can be found in Kistler's webpage. The PSFC-problem originated in the erroneous conversion of the recording format for the observed values of surface pressure and mean sea level pressure. Due to an error in handling the decimal points, most of the observations within the 1000 mb contour were rejected as unrealistically high pressure. This problem affects only the NCEP reanalysis data for the period of 1948 to 1967. The erroneous omission of the observed data causes the data assimilation process to completely determine the details of the surface pressure field without the benefit of direct measurement when the pressure went below 1000 mb. A case study by Kistler showed that maximum impact of this problem appears in the northeast Asia in July due to the constancy of the Asian Monsoon heat lows. Over the northeast Asia, corrected surface pressure should be within a few millibars lower than the current values in the NCEP reanalysis data, which means the convergence and cyclonic circulation in the lower troposphere should be stronger during the 1948-67 period. Thus, this error actually reduced the magnitude of the signal described here and

could not be the main cause of the interdecadal change over the northeast China. The problem of “spurious moisture sink/source” comes from an inappropriate approximation for the humidity diffusion in the AGCM used by the NCEP reanalysis. The error may have induced false increase/decrease in atmospheric humidity and precipitation, and affect local moisture budget and cloud cover. The spurious moisture sink/source makes larger impact where the local vertical moisture gradient is larger than the vertical gradient of the global average. This can be one of the possible reasons why the NCEP reanalysis data give too much summer precipitation over the sub-Saharan region for the period of late 1950’s to late 1960’s.

Systematic bias in the AGCM

The NCEP reanalysis applies continuously in time, a 3-dimensional variational method with an AGCM to realize 4-dimensional data assimilation (Parrish and Derber, 1992). Gaps in the 4-dimensional world that observations do not cover are filled with model calculations. In data-void region/time, the reanalysis data become more model-dependent. It has been noticed that the reanalysis data tend to overestimate precipitation over the places where the model climate is colder and drier than the real climate (Kalnay *et al.*, 1996, Trenberth and Guillemot, 1998). On the other hand, there are several significant increases in the total number of observations (and spatial and temporal coverage and density) included in the NCEP reanalysis during the 50-year period since 1948. For example, an increase in the quantity of observation took place in the late 1960’s due to the increase in land surface synoptic reports, ocean ship reports, radiosondes and aircraft reports (Kistler and Kalnay, 1999). Such a change in the quantity of observations may lead to a shift in mean climate state in the NCEP reanalysis data from a more model-climate before the late 1960’s to a more real climate after then. This possible artificial factor could contribute to unrealistic features on interdecadal time scales in the NCEP reanalysis data. However, it appears that the impact of this problem has merely amplified, rather than created the interdecadal changes in the Asia and Africa summer monsoon, because the timing, the sign of the trends, and the spatial pattern over the regions of east Asia of the interdecadal change in precipitation derived from the NCEP reanalysis data show good agreement with the analysis of station observations in the Sahel and east China regions. A study by Chelliah (1999) indicated that independent observed precipitation, and radionsonde based wind and temperature measurements over Africa and South America support the interdecadal change shown in the NCEP reanalysis.

Role of SST

The great intensification of the divergence (convergence) in the lower (upper) troposphere over the central tropical Pacific Ocean in the NCEP reanalysis is a feature that one would not expect to see in an AGCM simulation with only the forcing of SST. Generally, AGCM simulations forced by SST show an increase of precipitation over the tropical Pacific ocean where SST becomes warmer. However, during the JJA season, the SST became slightly colder in central tropical Pacific Ocean (Fig. 8). We have also examined two AGCM 50-year simulations, one uses the NCAR Community Climate Model version 3 (CCM3), and the other uses a modified version of AGCM of European Center for Medium-Range Forecast (ECMWF) by the University of Hamburg (ECHAM), both of

which used observed temporal evolution in SST for the period from 1950 to 1999 as prescribed boundary condition. Both of these AGCMs are much less sensitive to the slight lowering of central tropical Pacific SST. With only the SST forcing of the atmospheric circulation, both models give a general trend of increased precipitation over the western to central tropical Pacific Ocean (west of about 170°W), and a decrease in precipitation over the tropical Pacific Ocean between about 160°W to 130°W (the decrease is very small in the ECHAM simulation). However, the two models give quite different pictures for the interdecadal changes in the Asia and Africa summer monsoon. The ECHAM shows a slight decrease in precipitation over north Africa and almost no change over east China while the CCM3 shows a slightly increase in the precipitation over the north Africa and east China. The correct trend in the change of precipitation over north Africa in the ECHAM simulation is probably due to the large increase in the simulated summer precipitation over southeast Asia during the period of 1968-99 which is somewhat similar to the feature shown from the NCEP reanalysis. The uncertainty in the interdecadal changes in the simulation of the monsoon with only SST forcing also suggests that the interdecadal change in the Asia-Africa summer monsoon may not be very sensitive to the change in the tropical Pacific SST. A recent study by Hoerling et al. (2000) also suggest an important role of SST changes in the Indo-Pacific region in modulating Atlantic Ocean circulation and SST patterns, which could then influence precipitation changes in the Sahel region. Hence it is possible that the persistent development of the drought in the north Africa which has tied to changes in Atlantic Ocean SST could also have an important Indian Ocean link.

Role of climate change over land

It is possible that the reanalysis data give a better picture of change in Asia-Africa summer monsoon compared to the AGCM simulations discussed above, which may give a better simulation of the changes over the tropical Pacific Ocean. The results highlight the important role for regional climate changes of land surface processes, which appear to be less realistic in SST-forced AGCM simulations. The representation of these land surface process, such as suggested by Charney (1975), are a very important factor in the persistent drought in the Sahel region. It is possible that the NCEP reanalysis data give a good representation of the African drought because the influence of the land surface processes are included indirectly by the assimilation of actual observations.

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References

- Allan, R.J., J.A., Lindesay, and C.J.C., Reason, 1995: Multidecadal variability in the climate system over the Indian Ocean region during the Austral summer, *J. Climate*, **8**, 1853-1873.
- Charney, J.G., 1975: Dynamics of deserts and drought in the Sahel. *Quart. J. Roy. Meteor. Soc.*, **101**, 193-202.
- Charney, J.G., P.H. Stone, and W. J. Quirk, 1975: Drought in the Sahara: A biogeophysical feedback mechanism. *Science*, **187**, 434-435.
- Chelliah, M., 1999: Climate shift-like variations in the late 1960's and early 1970's: is it real or is it reanalysis ? *Proc. The 24th Annual Climate Diagnostics and Prediction Workshop, Tucson, Arizona, November 5-9, 1999*, 347-350
- Derber, J.D., D.F. Parrish, and S.J. Lord, 1991: The new global operational analysis system at the National Meteorological Center, *Wea. Forecasting*, **6**, 538-547.
- Diaz, H.F., 1986: An analysis of twentieth century climate fluctuations in northern North America, *J. Climate. and Appl. Meteorol.*, **25**, 1625-1657.
- Dronia, H., 1974: *The Climate of Europe: Past, Present and Future*, edited by H. Flohn and R. Fantechi, D. Reidel publishing Company, 1984, 356pp.
- Fu, Congbin, H. F. Diaz, and J. Fletcher, 1989, Changes of atmospheric circulation over Northern Hemispheric Ocean associated with rapid global warming in 1920's, *NOAA, TN*. 45pp.
- Graham, N.E., T.P. Barnett, and R. Wilde, 1994: On the roles of tropical and midlatitude SSTs in forcing interannual to interdecadal variability in the winter Northern Hemisphere circulation, *J. Climate*, **7**, 1416-1441.
- Guo, Qiyun, 1983: Variations in the East Asia summer monsoon index, *DiLiXueBao*, **38**, 207-217.
- Kalnay, E., et al, 1996: The NCEP/NCAR 40-Year reanalysis project, *Bull. Amer. Meteo. Soc.*, **77**, 437-471.
- Kistler, R. and E. Kalnay, 1999: Reanalysis prior to 1958, <http://lnx21.wwb.noaa.gov/images/conf2/conf2.html>.
- Lamb, P.J., 1982: Persistence of Subsahara drought, *Nature*, **299**, 46.
- Lamb, P. J., 1983: Sub-Sahara rainfall update for 1982: continued drought, *J. Climatology*, **3**, 419-422.
- Parrish, D.F., and J.C. Derber, 1992: The National Meteorological Center's spectral statistical interpolation analysis system. *Mon. Wea. Rev.*, **120**, 1747-1763.
- Tao, S.-Y., Fu, C.-B., Zeng, Z.-M., and Zhang, Q.-Y., 1991: Two long-term instrumental climatic data bases of the People's Republic of China, *ORNL/CDIAC-47, NDP-039*, Carbon Dioxide Information Analysis center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Trenberth, K.E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere, *Bull. Amer. Meteo. Soc.*, **71**, 988-993.
- Trenberth, K.E., J.W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific, *Climate Dyn.*, **9**, 303-319.

- Trenberth, K.E., and C.J. Guillemot, 1998: Evaluation of the atmospheric moisture and hydrological cycle in the NCEP/NCAR reanalysis, *Climate Dyn.*, **14**, 213-231.
- Trenberth, K.E., D.P., Stepaniak, and J. M., Caron, 2000, The global monsoon as seen in the divergent atmospheric circulation, *J. Climate*, **13**, 3969-3993.
- Wang, B., 1995: Interdecadal changes in El Nino onset in the last four decades, *J. Climate*, **8**, 267-285.
- Yan, Z.-W., J.-J. Ji, and D.-Z. Ye, 1989: The abrupt climate change of northern hemispheric summer monsoon during 1960's, *ZhongGuoKeXue*, **33(B)**, 97-103
- Zhang, Y., J.M. Wallace, and D. S. Battisti, 1996: ENSO-like decade-to-century scale variability: 1900-93, *J. Climate*, **9**, 1468-1478.

Figure Captions

Fig.1 Interdecadal change in summer (JJA) precipitation observed at 205 stations in China. The large “-” sign indicates HeZe station (35.25°N, 115.43°E), and the large “+” sign, HuangShi station (30.25°N, 115.05°E). These two sites are representative of strong decadal shifts in precipitation. Units of mm/month.

Fig.2 Interdecadal change in summer (JJA) precipitation in the NCEP reanalysis. The locations of HeZe and HuangShi stations are indicated by an ‘X’ in the plot. Units of mm/month.

Fig.3 Time-series of normalized anomalous summer (JJA) precipitation. Standardized units.

Fig.4 Differences between the means for two periods, 1968-99 minus 1948-67, in the velocity potential at (a) 200 mb, units $5 \times 10^4 \text{ m}^2/\text{s}$; and (b) 850 mb, units $2 \times 10^4 \text{ m}^2/\text{s}$. Arrows indicate the divergent wind derived from the differences in the velocity potential field.

Fig.5 Time series of normalized anomalous velocity potential. Standardized units.

Fig.6 Differences between the means for two periods: 1968-99 minus 1948-67, in the streamfunction at (a) 200 mb, units $10^6 \text{ m}^2/\text{s}$; and (b) 850 mb, units $5 \times 10^4 \text{ m}^2/\text{s}$. Arrows indicate the rotational wind derived from the differences in the streamfunction.

Fig.7 Time-series of normalized anomalous streamfunction. Standardized units.

Fig.8 Difference in JJA mean sea surface temperature (SST) for two periods: 1968-99 minus 1948-67. Units in °C.

Station Precip.: 1968-93 minus 1948-67 JJA

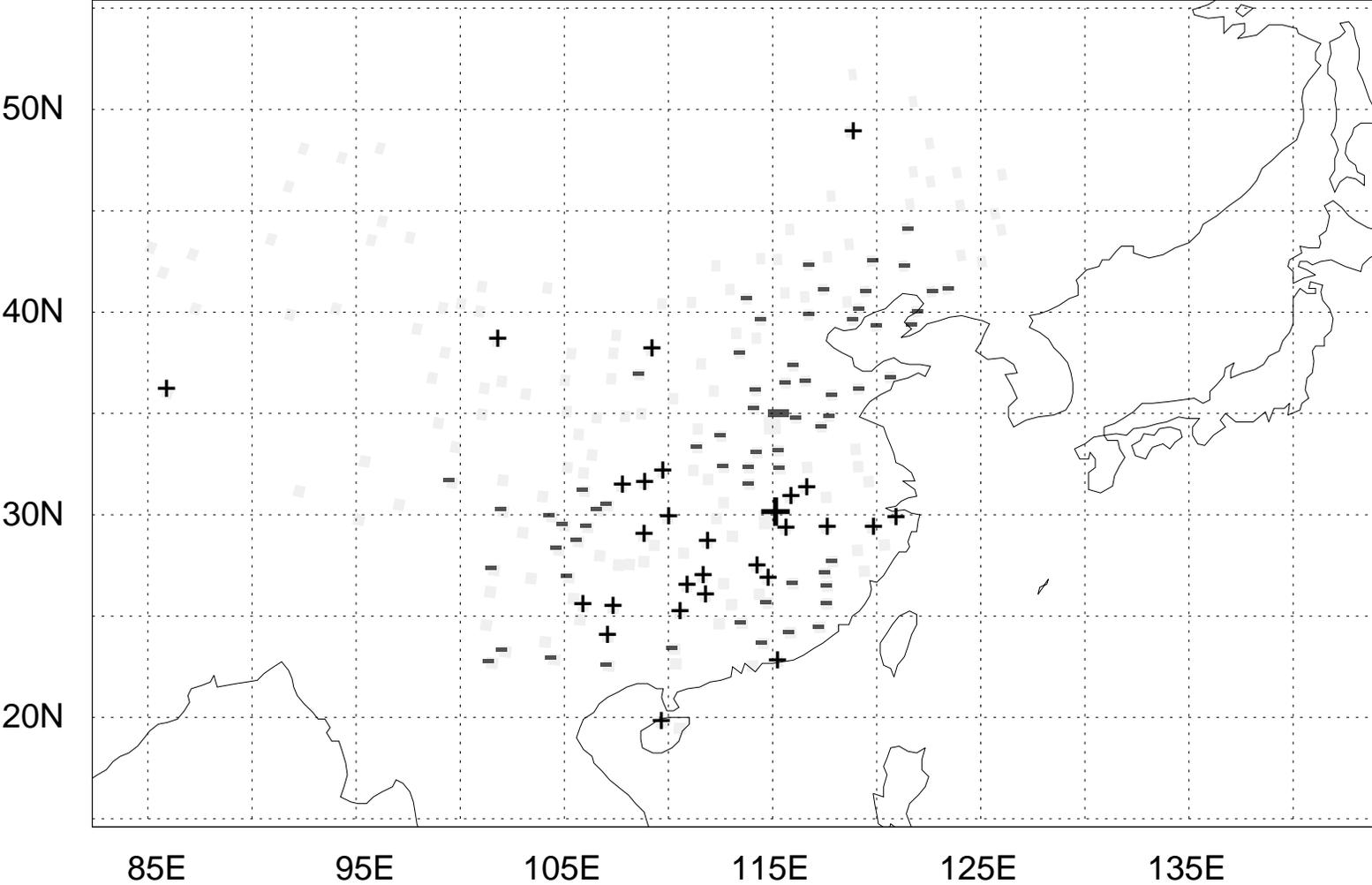


Figure 1

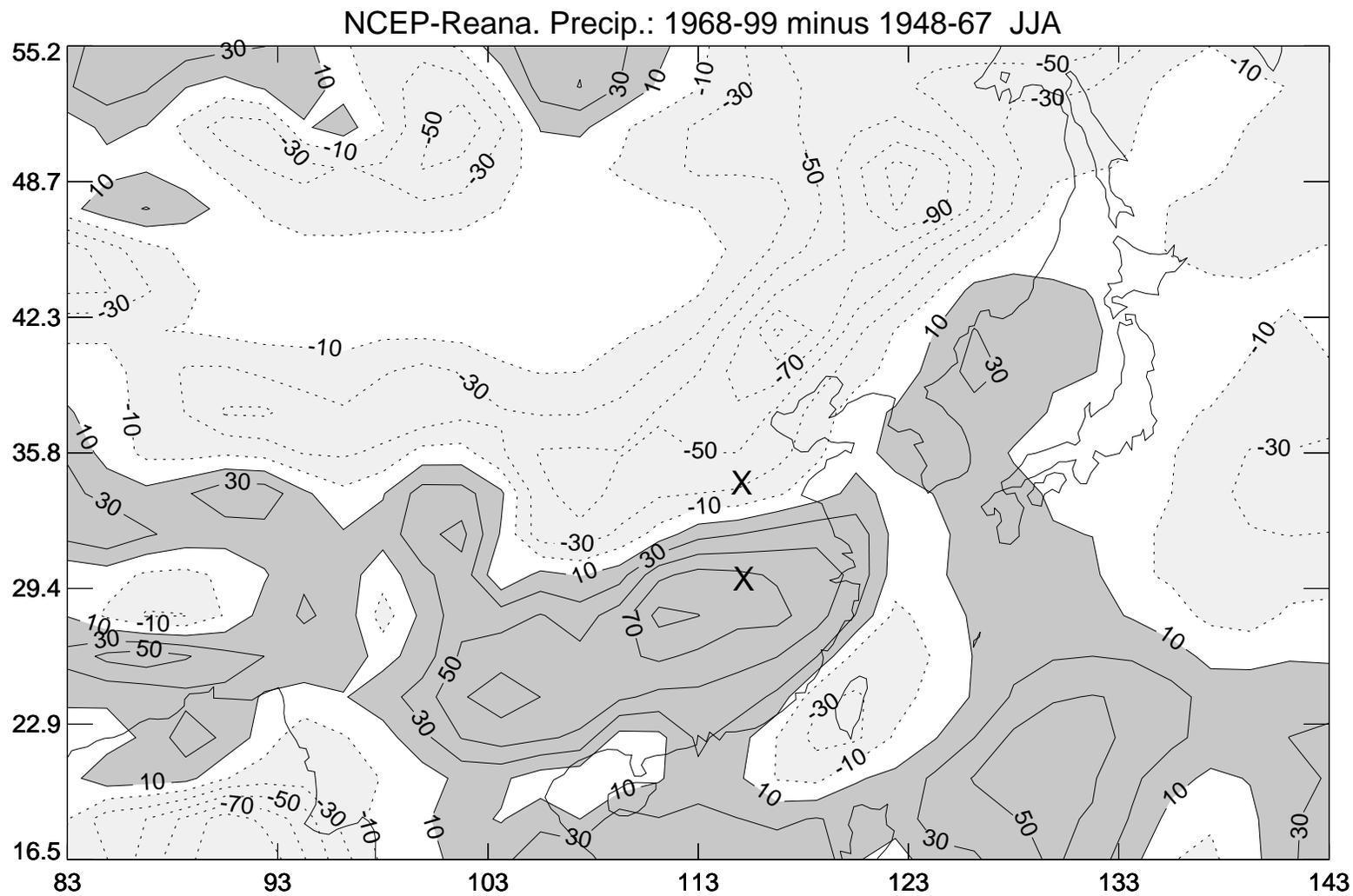


Fig. 2

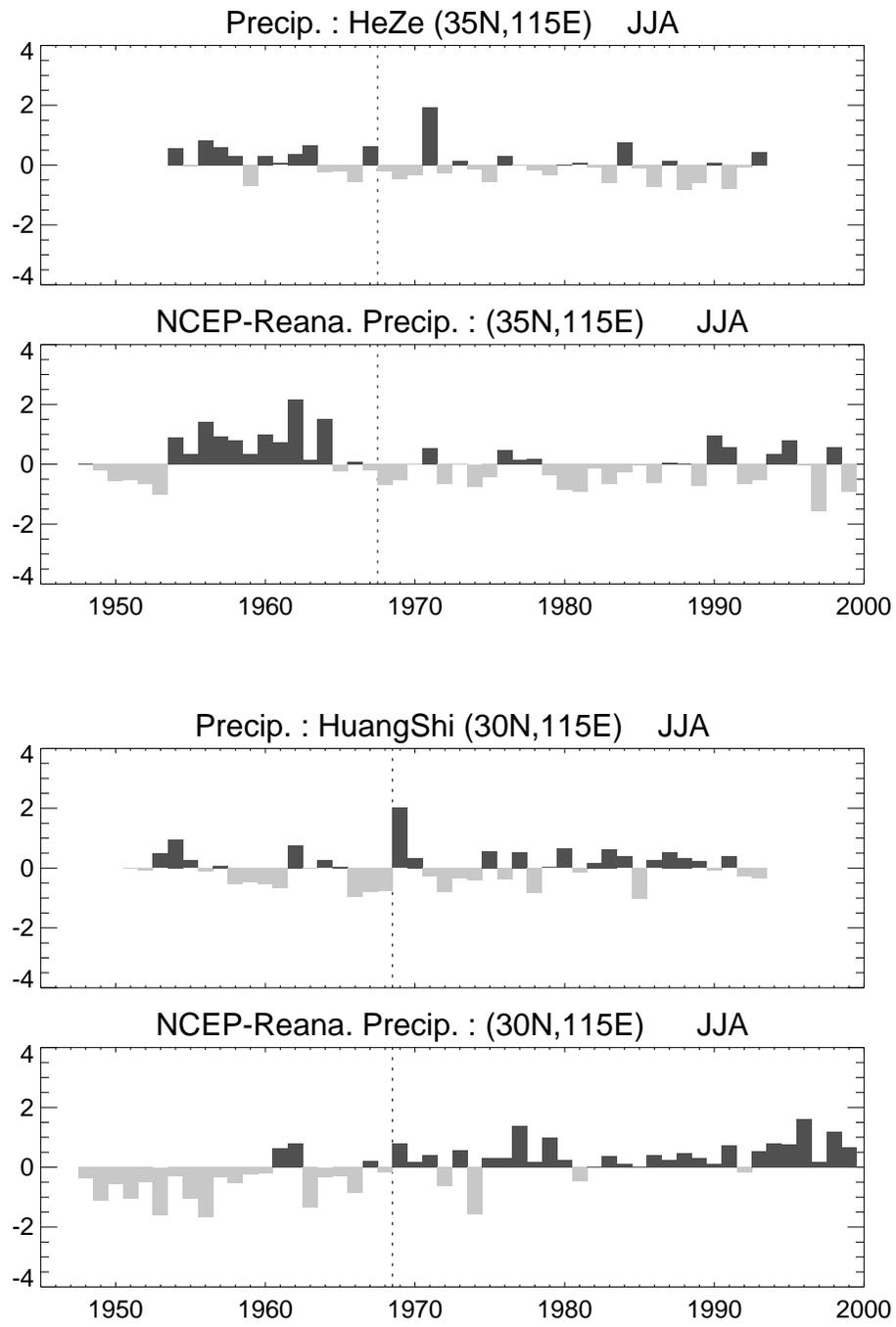


Fig. 3a

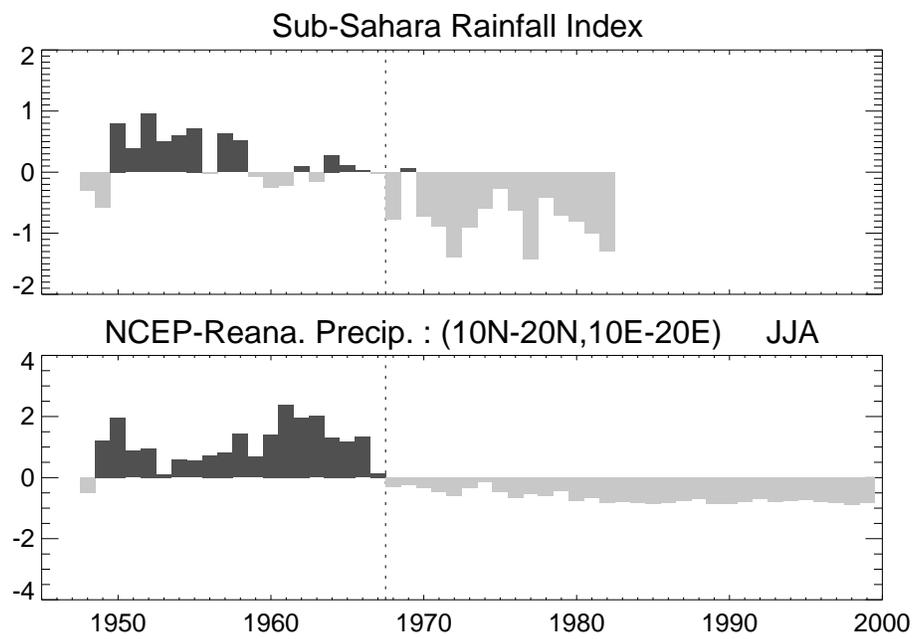


Fig.3b

200 mb Velocity Potential (Chi): 1968-99 minus 1948-67 JJA NCEP-Rean.

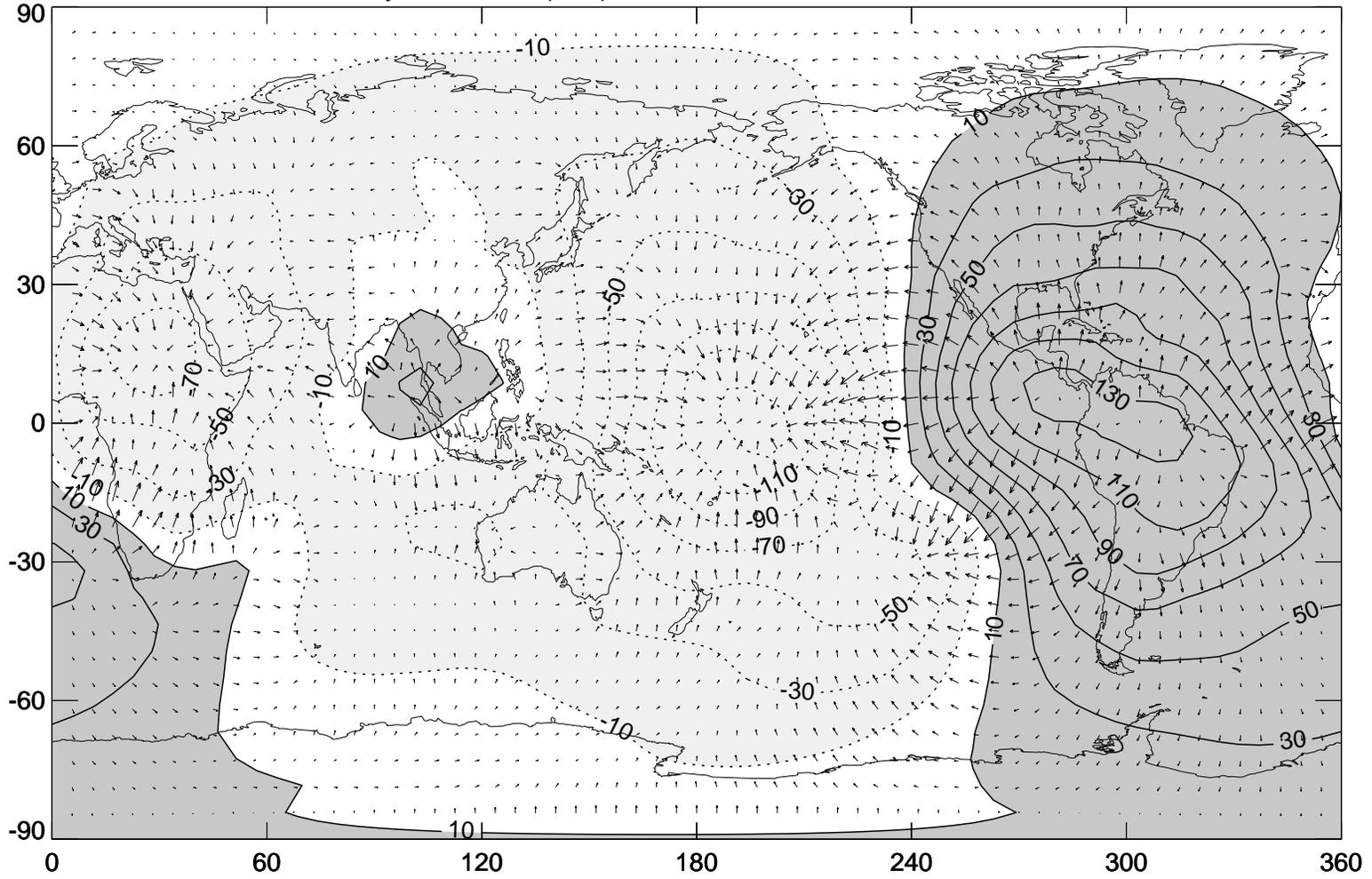


Fig.4a

850 mb Velocity Potential (Chi): 1968-99 minus 1948-67 JJA NCEP-Rean.

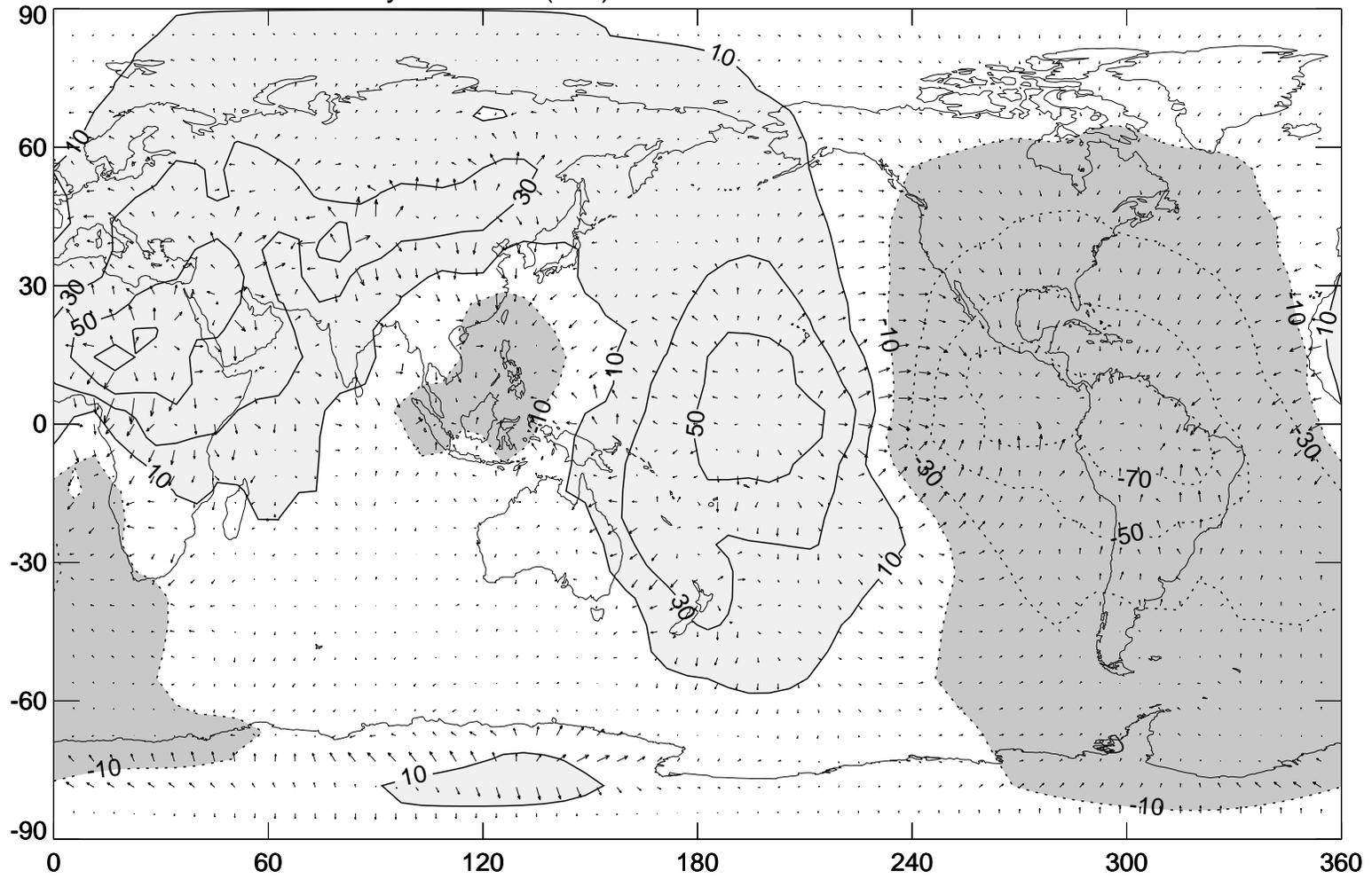


Fig.4b

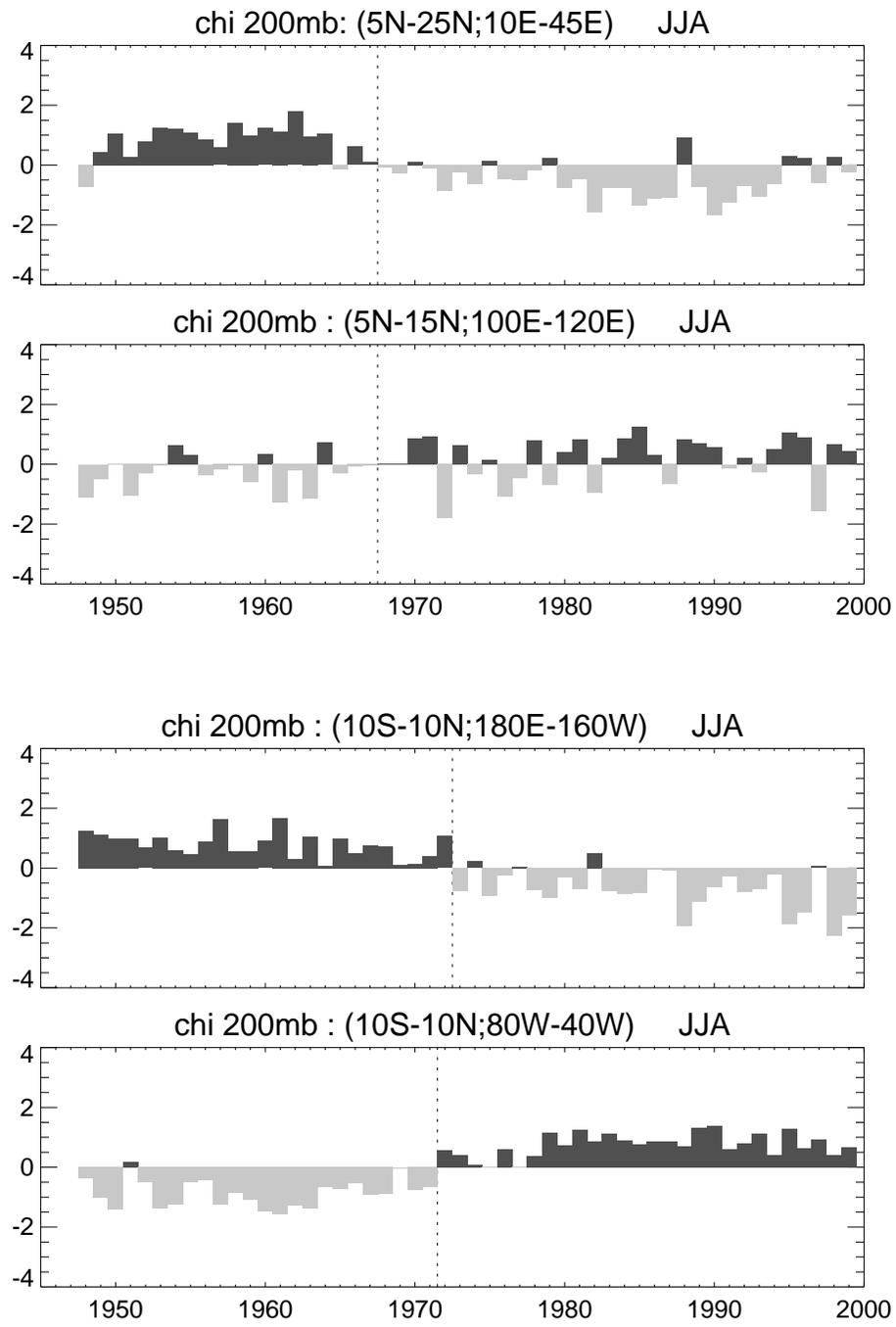


Fig.5

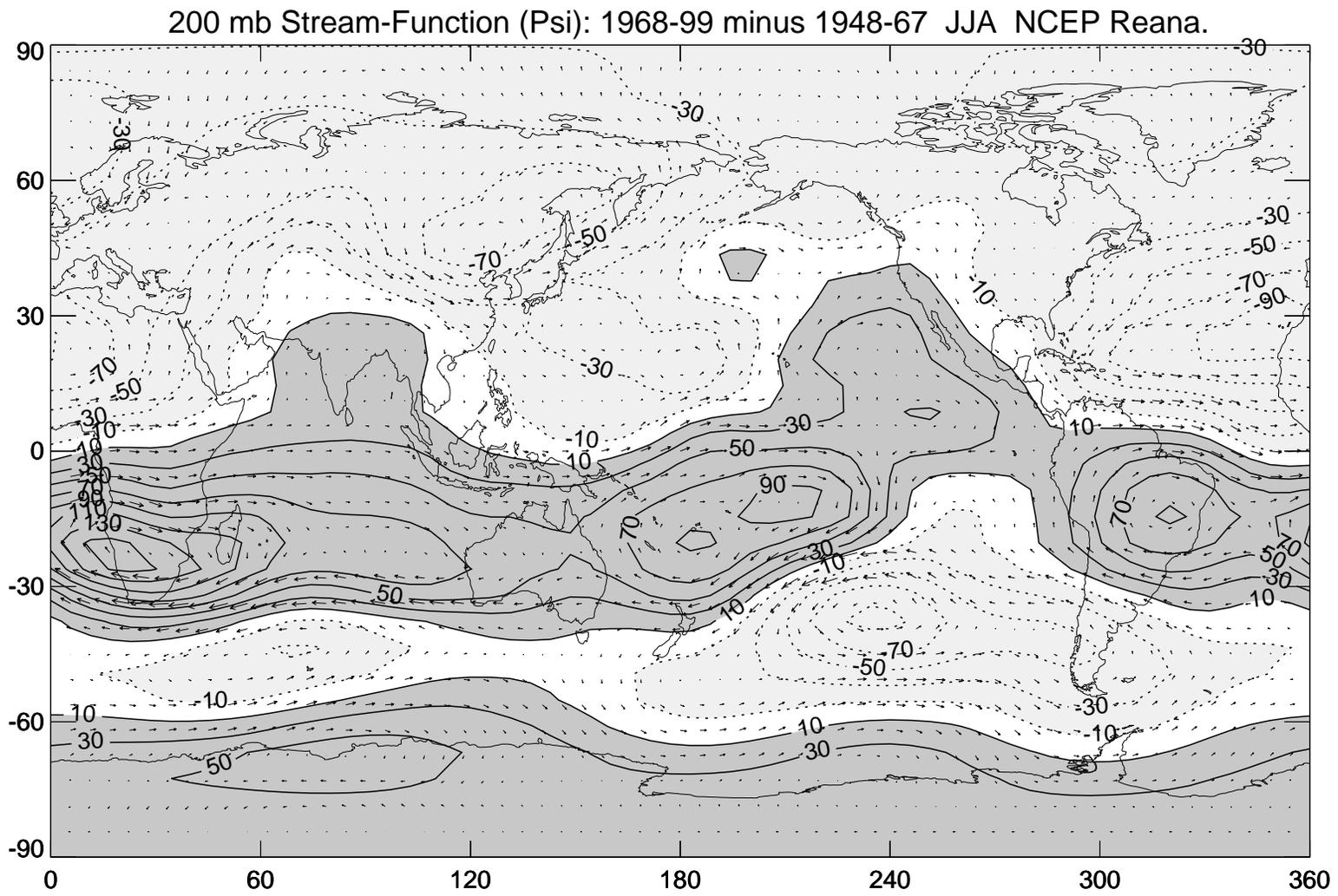


Fig.6a

850 mb Stream-Function (Psi): 1968-99 minus 1948-67 JJA NCEP Reana.

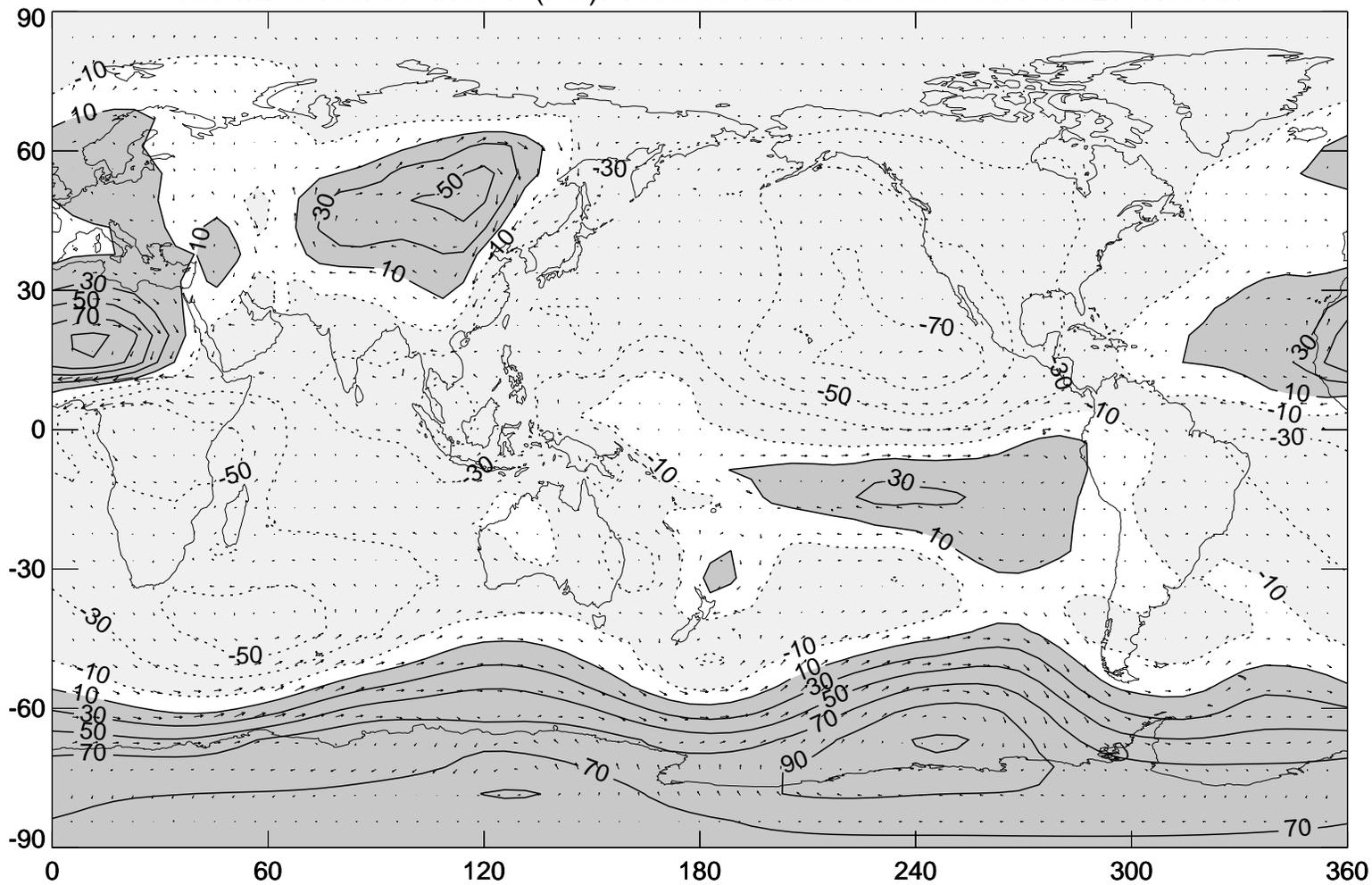


Fig.6b

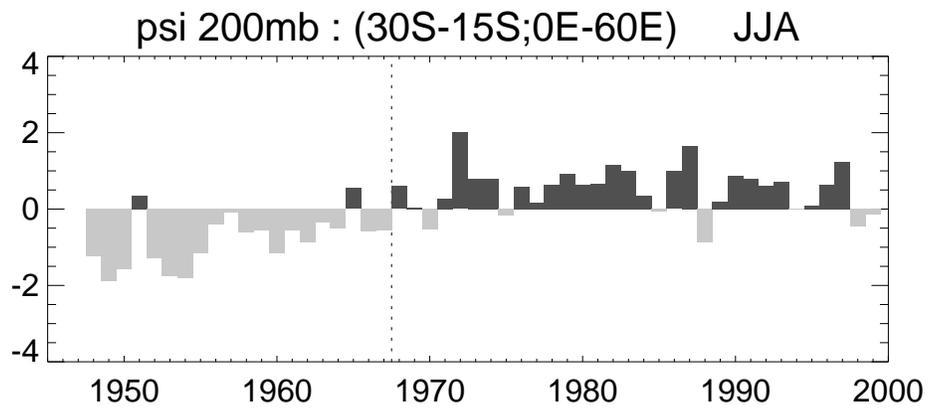
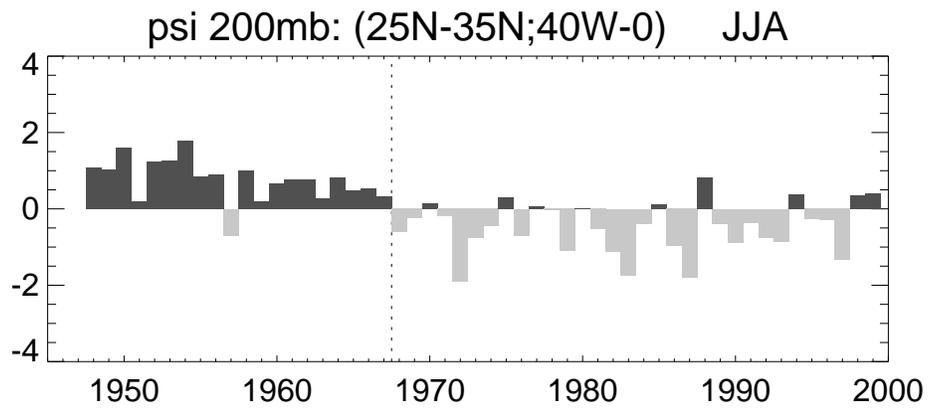
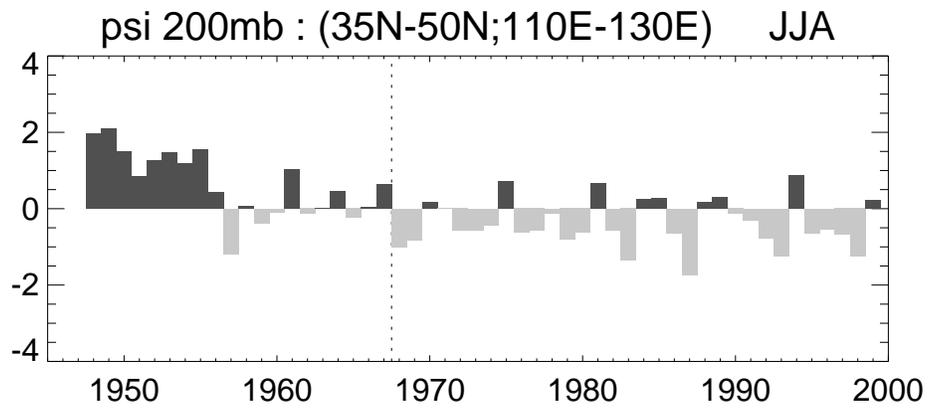


Fig.7a

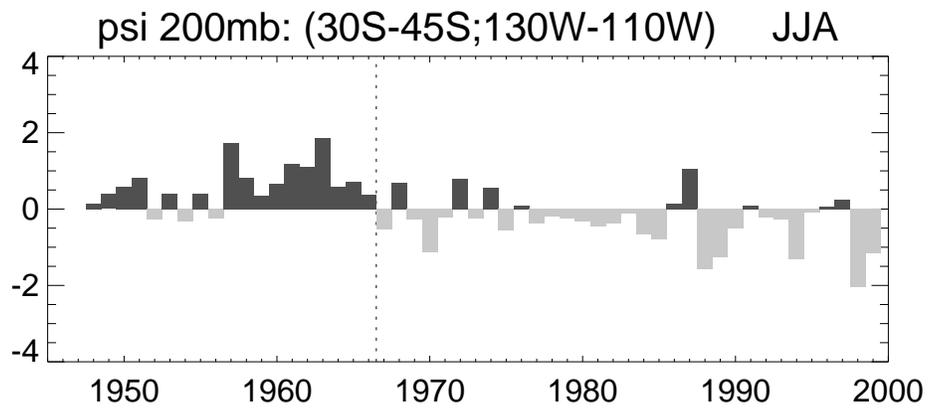
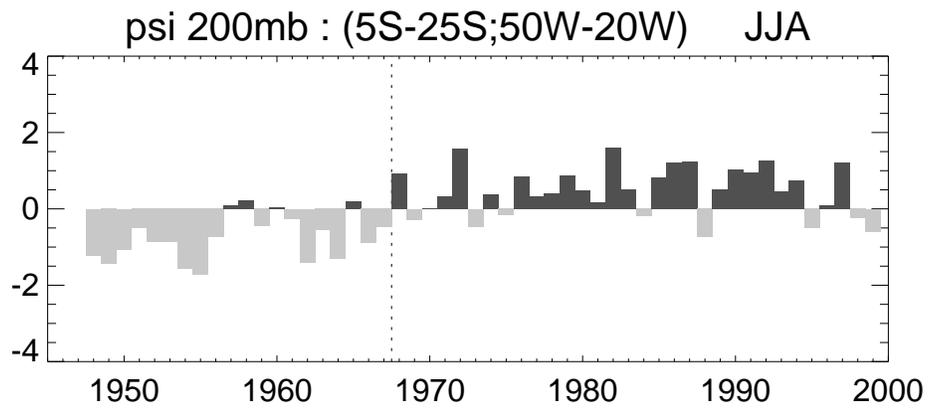
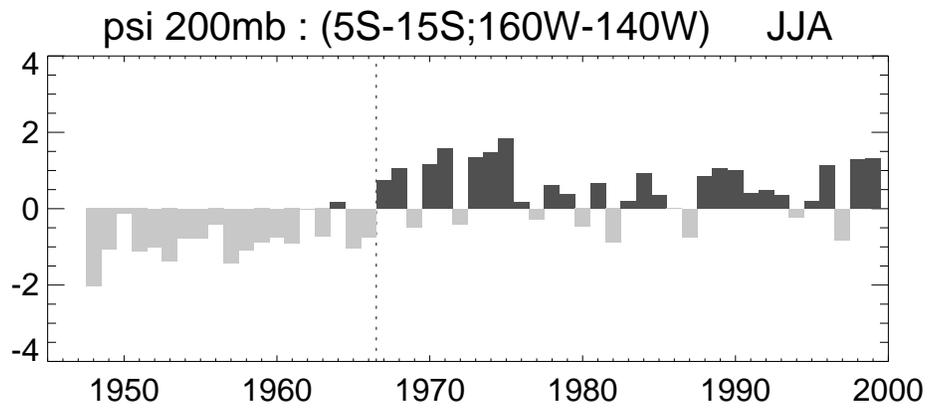


Fig.7b

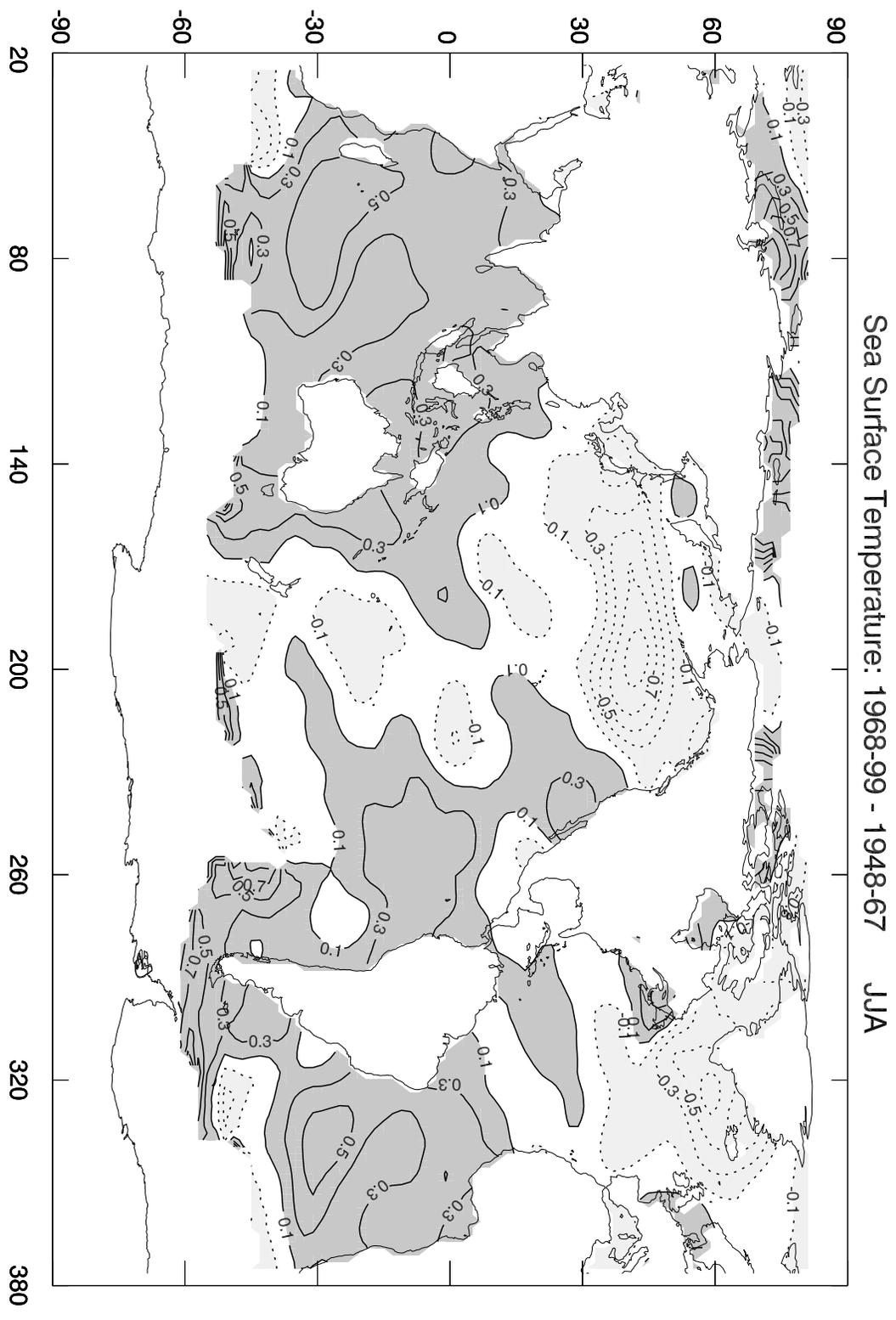


Fig.8